

METHOD AND APPARATUS FOR REPAIRING LITHOGRAPHY MASKS USING A CHARGED PARTICLE BEAM SYSTEM

5 [1000] This application is a continuation-in-part of U.S. Pat. App. 09/522,561, filed March 10, 2000.

Technical Field of the Invention

10 [1001] The present invention relates to the field of charged particle beam processing and, in particular, to a method and apparatus for removing material from a semiconductor lithography mask.

Background and Summary of the Invention

15 [1002] Focused ion beam (FIB) systems are widely used in microscopic-scale manufacturing operations because of their ability to image, etch, mill, deposit, and analyze with great precision. Ion columns on FIB systems using gallium liquid metal ion sources (LMIS), for example, can provide five to seven nanometer lateral imaging resolution. Because of their versatility and precision, FIB systems have gained universal acceptance in the integrated circuit (IC) industry as necessary analytical tools for use in process development, lithography mask repair, failure
20 analysis, and defect characterization.

[1003] One step in the fabrication of integrated circuits entails the use of lithography. A semiconductor substrate on which circuits are being formed is typically coated with a material, such as a photoresist, that changes solubility when exposed to radiation. A lithography tool, such as a mask or reticle, positioned between the radiation source and the semiconductor substrate
25 casts a shadow to control which areas of the substrate are exposed to the radiation. After the exposure, the photoresist is removed from either the exposed or the unexposed areas, leaving a

patterned layer of photoresist on the wafer that protects parts of the wafer during a subsequent etching or diffusion process.

[1004] The term mask is used generically herein to refer to any lithography tool, regardless of the type of exposing radiation and regardless of whether the image of the mask is printed once or stepped across the substrate. A mask typically comprises a patterned layer of an absorber material, such as chromium or molybdenum silicide, on a substrate, such as quartz. When the pattern is formed on the mask, it is not unusual for the mask to have defects, such as having absorber material deposited in areas that should be clear, or having absorber missing from areas that should be opaque. The high resolution of FIB systems make them ideal for removing absorber from areas of a mask that should be clear.

[1005] The use of a FIB system for removing opaque material from a mask is described, for example, in U.S. Pat. No. 6,042 738 to Casey et al. for "Pattern Film Repair Using a Focused Particle Beam System," which is assigned to FEI Company, Hillsboro, Oregon the assignee of the present invention. FEI Company manufactures focused ion beam systems, such as the Model 800 Series FIB Systems, that have software specifically for facilitating mask repair.

[1006] When using a FIB system to remove opaque material from a mask, the mask is positioned on a stage that is maneuvered, for example, using positional information from a previous inspection, so that the defect is within the area scanned by the ion beam. The beam then scans the surface of the area around the defect to produce an image. The defect area is identified and the ion beam current is increased to remove the opaque material.

[1007] Ideally, after removal of inadvertently deposited absorber material, the substrate area from which the defect material was removed should have the same characteristics as the area would have had if the area had been manufactured without the defect. Unfortunately, the

removal process incidentally and unavoidably changes the properties of the substrate. For example, in a photolithography mask that uses a chromium absorber on a quartz substrate, the quartz at the location where the defect was removed typically loses some of its transparency. This loss is particularly severe for the very short exposing light wavelengths used in modern photolithography tools, with the loss of transparency, typically being between 3 percent and 10 percent.

[1008] Overetching, particularly at the edges of the repair, is a primary factor in the loss of transparency. This phenomenon is known as “riverbedding” because the etched edges resemble riverbeds when viewed with an electron microscope. One approach to minimizing the riverbed effect is to first remove the center portion of the opaque defect, and then apply a lower ion dose to the outside edges to complete the repair. This technique is known as a “framed repair.” The 800 Series FIB System from FEI Company can perform a framed repair to the operator’s specification. Even when using a framed repair, riverbeds are typically about 20 nm deep.

[1009] Other factors thought to contribute to loss of transparency include the implantation of gallium from the ion beam into the quartz substrate and damage to the quartz itself, due to etching past the chromium or due to crystalline damage caused by impact of the heavy gallium ions. U.S. Pat. No. 6,042,738 describes using a clean-up gas with the focused ion beam to improve the transparency of the substrate after removing an opaque defect.

Summary of the Invention

[1010] An object of the invention, therefore, is to remove material from a substrate while minimizing or eliminating changes in characteristics of the substrate.

[1011] Applicants have discovered that the effects on a substrate of the focused ion beam removal of material on the substrate is minimized if the ion beam moves initially in a pattern that

produces a uneven surface. For example, the beam could move in a pattern in which the sample is milled at a series of non-contiguous points to produce a series of holes, rather than moving in a conventional pattern of overlapping pixels. In a subsequent milling step, the beam moves in a pattern, such as a pattern of overlapping or nearly overlapping pixels, to produce a relatively uniform, planar surface. During the subsequent milling step, an etch enhancing gas is preferably used.

[1012] The present invention decreases the size of riverbeds and provides increased substrate transparency at the repaired area compared to prior art repair methods. In some embodiments, the invention reduced the amount of time that the mask needed to be under the ion beam, thereby improving production rates.

[1013] The invention is not limited to any particular type of mask or substrate materials, although the benefits of the invention are particularly apparent in milling chromium on a quartz substrate.

Brief Description of the Drawings

[1014] For a more complete understanding of the present invention, and the advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings, in which:

[1015] FIG. 1 shows schematically a typical focused ion beam system used in a preferred embodiment of the invention.

[1016] FIG. 2 is a flow chart showing a preferred method of the present invention.

[1017] FIG. 3 shows a portion of a mask, greatly enlarged, having an opaque defect.

Detailed Description of Preferred Embodiments

[1018] In FIG. 1, a focused ion beam system 8 includes an evacuated envelope 10 having an upper neck portion 12 within which are located a liquid metal ion source 14 and a focusing column 16 including extractor electrodes and an electrostatic optical system. Ion beam 18 passes from source 14 through column 16 and between electrostatic deflection means schematically indicated at 20 toward sample 22, which comprises, for example, a photolithography mask positioned on movable X-Y stage 24 within lower chamber 26. An ion pump 28 is employed for evacuating neck portion 12. The chamber 26 is evacuated with turbomolecular and mechanical pumping system 30 under the control of vacuum controller 32. The vacuum system provides within chamber 26 a vacuum of between approximately 1×10^{-7} Torr and 5×10^{-4} Torr. When an etch-assisting or an etch retarding gas is used, the chamber background pressure is typically about 1×10^{-5} Torr.

[1019] High voltage power supply 34 is connected to liquid metal ion source 14 as well as to appropriate electrodes in focusing column 16 for forming an approximately 1 keV to 60 keV ion beam 18 and directing the same downwardly. Deflection controller and amplifier 36, operated in accordance with a prescribed pattern provided by pattern generator 38, is coupled to deflection plates 20 whereby beam 18 may be controlled to trace out a corresponding pattern on the upper surface of sample 22. The pattern to be traced is described in detail below. In some systems the deflection plates are placed before the final lens, as is well known in the art.

[1020] The source 14 typically provides a metal ion beam of gallium, although other ion sources, such as a multicusp or other plasma ion source, can be used. The source typically is capable of being focused into a sub one-tenth micron wide beam at sample 22 for either modifying the surface 22 by ion milling, enhanced etch, material deposition, or for the purpose

of imaging the surface 22. An charged particle multiplier 40 used for detecting secondary ion or electron emission for imaging is connected to video circuit and amplifier 42, the latter supplying drive for video monitor 44 also receiving deflection signals from controller 36. The location of charged particle multiplier 40 within chamber 26 can vary in different embodiments. For
5 example, a preferred charged particle multiplier 40 can be coaxial with the ion beam and include a hole for allowing the ion beam to pass. A scanning electron microscope 41, along with its power supply and controls 45, are optionally provided with the FIB system 8.

[1021] A fluid delivery system 46 optionally extends into lower chamber 26 for introducing and directing a gaseous vapor toward sample 22. U.S. Pat. No. 5,851,413 to Casella et al. for
10 "Gas Delivery Systems For Particle Beam Processing," assigned to the assignee of the present invention, describes a suitable fluid delivery system 46.

[1022] A door 60 is opened for inserting sample 22 on stage 24 which may be heated or cooled, and also for servicing the reservoir 50. The door is interlocked so that it cannot be opened if the system is under vacuum. The high voltage power supply provides an appropriate
15 acceleration voltage to electrodes in ion beam column 16 for energizing and focusing ion beam 18. When it strikes the sample, material is sputtered, that is physically ejected, from the sample. Focused ion beam systems are commercially available, for example, from FEI Company, Hillsboro, Oregon, the assignee of the present application.

[1023] In a preferred embodiment of the present invention, signals applied to deflection
20 controller and amplifier 36 cause the focused ion beam to move within a defect area on a mask in a manner that reduces the effect of the repair on the mask.

[1024] FIG. 2 is a flow chart showing steps of a preferred embodiment of the present invention. Step 212 shows that the stage is moved or navigated so that the defect is under the ion

beam. In step 214, a defect area is designated. Various techniques can be used to designate the defect area. For example, in an FEI Accura Series FIB system using the IntuitION™ software, the defect area is designated by first drawing a box on the display that includes both the opaque defect and clear, non-defect areas. The opaque areas appear brighter on the display screen, because the secondary electron current coming from the chromium area is greater than the secondary electron current coming from the quartz areas. To designate the defect area, the system automatically identifies the defective, opaque area by the larger secondary electron current. If necessary, the system operator can adjust the threshold used by the system to differentiate between defect and clear areas, and can also manually adjust the designated defect area. The IntuitION™ software includes an “Edge Lock” feature that will automatically align an edge of the designated defect area with a reference edge of opaque material, so that the repair will remove material up to, but not past the reference edge.

[1025] In step 216, a “frame” or border is designated within the defect area. The frame preferably has a width of about two pixels, although the preferred width of the frame may vary with the mask construction. FIG. 3 shows an enlarged portion of a mask 310 having an opaque region 314, a clear region 316, and an opaque defect region 318, with a frame area 320 designated within opaque defect region 318. The IntuitION™ software allows the operator to set a frame width. If the Edge Lock feature was used, a Edge Lock Factor of, for example, -0.1, can be used to provide a similar border area 321 adjacent to a reference edge 322.

[1026] In step 220, the ion beam is directed to the defect region 318, excluding the frame area 320 and 321, to begin removing the defect and to produce an uneven surface. In a preferred embodiment, the pixel or dwell point spacing in step 220 is greater than the beam spot size to produce a series of holes in defect region 318. The pixel spacing is preferably between about 2

and 15 times the beam diameter or spot size, measured as the diameter at which the beam intensity falls to fifty percent of the maximum intensity. For example, pixel spacings of between 75 nm and 175 nm were used successfully with a preferred 35 nm beam diameter, although the preferred spacing will depend upon the application.

5 [1027] The pixel spacing should preferably be such as to provide a hilly texture to the milled surface, that is, not so great that large flat areas remain and not so small that the milled area is flat after step 220. Experimental results show the transparency of the repaired area is not particularly sensitive to the exact pixel spacing used. Because the ion beam intensity typically has a Gaussian or “bell-shaped” current density distribution, the holes are also Gaussian shaped, and the peaks of the regions between the holes may also be milled so that they are lower than their height before step 220.

10 [1028] Step 220 produces an uneven surface, that is, a surface with topography variations significant enough to enhance ion beam milling. The minimum level of unevenness can vary with the thickness and type of the material being milled. The preferred variation in surface topography is greater than 50 nm and more preferably greater than 70 nm.

15 [1029] The ion beam spot size can be increased to about 0.15 μm for some implementations, and beams as large as 0.8 μm or larger can be achieved if desired. If the Framed Repair option in the IntuitION™ software was used, it is necessary to cancel the repair after milling the interior of defect 318 so that the frame 320 is not milled in step 220.

20 [1030] The milling in step 220 is preferably performed without the use of an etch-assisting gas. By not using a gas in step 220, the time interval at which the ion beam can return to each pixel, that is, the refresh time, can be decreased because it is unnecessary to wait for additional gas molecules to be adsorbed onto the substrate surface. The ion beam dwell time can also be

increased, because it is not limited by the amount of adsorbed gas available at the dwell point. The repair time can therefore be significantly reduced. In one test, repair time was reduced by fifteen percent.

[1031] In step 220, the holes in the chromium were milled to between about seventy percent
5 and about ninety percent of the chromium thickness. It is desirable to mill a large portion of the chromium depth in step 220 because milling is relatively rapid, but the depth of milling should not be so great that the chromium is thinned to a point at which a significant amount of gallium is implanted in the substrate. A value in the of 50% to 95% of the depth may be useful in many applications, and a value outside this range may be useful in some applications. The optimum
10 pixel spacing and depth of milling in step 220 will depend on the beam size and properties of the mask, such as the absorber and substrate materials and the thickness of the absorber.

[1032] In step 224, the ion beam is directed to pixels within the entire defect area, including
15 frame area 320 and 321 using a pixel spacing sufficiently small to produce a smooth floor on the milled area. If the Edge Lock feature is used, the Edge Lock Factor is now set to zero so that the milling extends to the reference edge 322. While the ion beam is applied in step 224, an etch-
20 enhancing gas is preferably directed to the impact area of the ion beam to assist in milling. Etch enhancing gases may include halogens and are typically specific to the particular material being etched. A preferred etch enhancing gas for etching chromium comprises molecular bromine. Xenon-difluoride would be suitable for etching MoSiON and other attenuating materials well.
25 Water vapor can be added to the bromine or other etchant, preferably at a 10:1 molar ratio of bromine to water, to reduce quartz etching.

[1033] One or more additional intermediate milling steps can be used between step 220 and step 224. The intermediate steps typically use a pixel spacing between that of step 220 and that

of step 224. If multiple intermediate steps are used, the pixel spacing typically decreases with each subsequent step. Some of the holes milled in the various steps will typically overlap previously milled holes. Upon finishing the multiple steps, however, the amount of material removed from each point in the sample is approximately equal to produce a relatively uniform, planar floor over the entire area milled .

[1034] In both steps 220 and 224, the ion beam moves between pixel locations, dwelling at each pixel location for a predetermined dwell time, and returning to each location periodically until a prescribed ion dose has been delivered. The same pixel spacing and dosages are typically used for defects of various sizes, although these parameters, as well as other beam settings, can be changed for different applications. Both steps preferably employ a 75 μm aperture in the ion optical column and use a 35 pA beam current. In both steps, the beam preferably moves in a serpentine pattern, that is, the scanning direction is reversed at the end of each row scanned.

[1035] In one preferred embodiment, the beam dwells at each pixel location for approximately 500 μsec during step 220, and the minimum refresh time, that is, the minimum time permitted for the beam to return to a given pixel location in a subsequent scan, is set to about 10 μsec thereby minimizing the delay between rasters. In step 224, the pixel spacing is about 0.04 μm , and the dwell time is about 0.35 μsec . The refresh time is increased to about 6000 μsec to allow time for gas molecules to adsorb between successive rasters. In step 224, the operation can be programmed to pause after specified percentages, such as 40%, 60%, 80% or 90%, of the ion dose is delivered. This pause allows the system operator to view the progress of the repair and to ensure that the repair operation does not etch significantly into the substrate after the defect material is removed. In some embodiments, SIMS can be used to analyze the

[illegible][illegible]

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100																																																																																																																																																											
0	00000000	00000001	00000010	00000011	00000100	00000101	00000110	00000111	00001000	00001001	00001010	00001011	00001100	00001101	00001110	00001111	00010000	00010001	00010010	00010011	00010100	00010101	00010110	00010111	00011000	00011001	00011010	00011011	00011100	00011101	00011110	00011111	00100000	00100001	00100010	00100011	00100100	00100101	00100110	00100111	00101000	00101001	00101010	00101011	00101100	00101101	00101110	00101111	00110000	00110001	00110010	00110011	00110100	00110101	00110110	00110111	00111000	00111001	00111010	00111011	00111100	00111101	00111110	00111111	01000000	01000001	01000010	01000011	01000100	01000101	01000110	01000111	01001000	01001001	01001010	01001011	01001100	01001101	01001110	01001111	01010000	01010001	01010010	01010011	01010100	01010101	01010110	01010111	01011000	01011001	01011010	01011011	01011100	01011101	01011110	01011111	01100000	01100001	01100010	01100011	01100100	01100101	01100110	01100111	01101000	01101001	01101010	01101011	01101100	01101101	01101110	01101111	01110000	01110001	01110010	01110011	01110100	01110101	01110110	01110111	01111000	01111001	01111010	01111011	01111100	01111101	01111110	01111111	10000000	10000001	10000010	10000011	10000100	10000101	10000110	10000111	10001000	10001001	10001010	10001011	10001100	10001101	10001110	10001111	10010000	10010001	10010010	10010011	10010100	10010101	10010110	10010111	10011000	10011001	10011010	10011011	10011100	10011101	10011110	10011111	10100000	10100001	10100010	10100011	10100100	10100101	10100110	10100111	10101000	10101001	10101010	10101011	10101100	10101101	10101110	10101111	10110000	10110001	10110010	10110011	10110100	10110101	10110110	10110111	10111000	10111001	10111010	10111011	10111100	10111101	10111110	10111111	11000000	11000001	11000010	11000011	11000100	11000101	11000110	11000111	11001000	11001001	11001010	11001011	11001100	11001101	11001110	11001111	11010000	11010001	11010010	11010011	11010100	11010101	11010110	11010111	11011000	11011001	11011010	11011011	11011100	11011101	11011110	11011111	11100000	11100001	11100010	11100011	11100100	11100101	11100110	11100111	11101000	11101001	11101010	11101011	11101100	11101101	11101110	11101111	11110000	11110001	11110010	11110011	11110100	11110101	11110110	11110111	11111000	11111001	11111010	11111011	11111100	11111101	11111110	11111111

Parameter	Setting
Aperture	75 μm
Beam Current	35 pA
Dwell time	500 μsec
Retrace	10 μsec
Min. Refresh	10 μsec
Gas	None
Technique	Frames – Dose to Frame = 0.0 Frame width = 2x Pixel Spacing Edge Lock Factor = -0.1

Table 1. Constants for Step 220

Parameter	Setting
Aperture	75 μm
Beam Current	35 pA
Pixel Spacing	0.04 μm
Dwell time	0.35 μsec
Retrace	10 μsec
Min. Refresh	6000 μsec
Gas	Br Only – HCIG 1.8 e^{-5}
Technique	Intervals – 0.40, 0.60, 0.80, 0.90 Edge Lock = 0.0

Table 2. Constants for Step 224

	Pixel Spacing (nm)	Depth (% Cr)	Actual Ion Dose (nC/ μm^2)	Edge (nm)	Through Transparency (%) AIMS	Transverse Transparency (%) AIMS	Riverbed Min Depth (nm)	Riverbed Max Depth (nm)
1	175	0.8	0.106	3.3	99.3	99	10	-2
2	175	0.9	0.119	4.5	96.7	96.7	-2	-10
3	125	0.9	0.14	9.9	98.8	96.9	-13	-25
4	100	0.8	0.246	28.3	97.6	95.1	-7	-30
5	150	0.8	0.114	17.7	98.6	95.9	-5	-12
6	150	0.9	0.129	12	98.1	95.5	-8	-17
7	100	0.9	0.277	4.2	98.4	95.4	-1	-20
8	75	0.7	0.328	-5.7	97.8	95.5	-7	-17
9	100	0.7	0.216	19.2	97.8	96.1	4	-4
10	75	0.9	0.422	15	98	93.8	-13	-14
11	125	0.8	0.124	24.2	97.7	94.9	-2	-7
12	75	0.8	0.375	3	98.8	95.7	-2	-2
13	175	0.7	0.092	34	96.7	95.2	9	11
14	150	0.7	0.1	5.4	97	93.4	1	1
15	125	0.7	0.109	-22.2	99	93.6	2	-8

TABLE 3

[1037] The transparencies were measured using light having a wavelength of 248 nm in an Aerial Image Measurement System (AIMS), and riverbed depths were measured using an atomic force microscope (AFM). “Through transparencies” were measured through the repaired region along a line perpendicular to the adjacent, non-defect, chromium line (e.g., line 322 of FIG. 3), and “transverse transparencies” were measured along a line parallel to the adjacent, non-defect, chromium line, through the repaired region. Positive values for riverbedding indicate residual material on the substrate, whereas negative values indicate a true riverbed or depressed area.

[1038] Riverbeds well under 20 nm were achieved, with riverbeds below 15 nm, below 10 nm, and even below 5 nm in many cases. Through transparencies were all greater than 95%, with most greater than 96% or 97%, and several greater than 98%. The “Edge” column of Table 3 indicates how closely the edge of the clear repaired region aligns with its intended edge, for example, line 322 of FIG. 3. The edge value is positive if the chromium line adjacent to the

repaired area is thicker than the same line away from repaired area and negative if the chromium line adjacent to the repaired area is thinner. In step 224, the chamber pressure was measured with a Hot Cathode Ionization Gauge (HGIG) to be 1.8×10^{-5} Torr. Applicants believe that the increase in transparency derives primarily from the reduction of riverbeds, rather than from reduced gallium implantation.

[1039] Applicants have also found that the milling specifications, that is, the pixel spacing, dose, ion energy, beam size, and other parameters, of each milling step box, as well as the number of steps used, may be varied to optimize milling depending on the mask characteristics, including the absorber material and thickness. The specification of each milling box and the number of boxes can be determined experimentally using the example and information provided above as a guide.

[1040] Although in the patterns described above, the milling is being performed in rectangular arrays of fixed pixel spacings within each box, the invention is not limited to that embodiment. For example, the pixel spacing can be gradually reduced, rather than being reduced in discrete steps, and the milling locations do not need to be distributed in a rectangular or regular pattern, so long as the pixels are spaced widely enough to preserve transparency and the amount of material eventually removed from each point is about the same to produce a flat, smooth, planar floor. The pixel spacing could even remain unchanged, with the pixel locations changing in subsequent scans to produce a flat, smooth, planar floor.

[1041] Although the invention has been described with respect to mask repair, it could be used in any application in which it is desired to remove material with minimal effect on the underlying material.

[1042] Where this application refers to removal of opaque material, it is intended to include other materials, such as phase-shifting materials, used on a mask.

[1043] Although the present invention and its advantages have been described in detail, it should be understood that various changes, substitutions and alterations can be made to the
5 embodiments described herein without departing from the spirit and scope of the invention as defined by the appended claims. Moreover, the scope of the present application is not intended to be limited to the particular embodiments of the process, machine, manufacture, composition of matter, means, methods and steps described in the specification. As one of ordinary skill in the
10 art will readily appreciate from the disclosure of the present invention, processes, machines, manufacture, compositions of matter, means, methods, or steps, presently existing or later to be developed that perform substantially the same function or achieve substantially the same result as the corresponding embodiments described herein may be utilized according to the present invention. Accordingly, the appended claims are intended to include within their scope such
15 processes, machines, manufacture, compositions of matter, means, methods, or steps.

[1044] We claim as follows: